The Dual-Readout Approach to Calorimetry

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Abstract

Simultaneous detection of the Čerenkov light and scintillation light produced in hadron showers makes it possible to measure the electromagnetic shower fraction event by event and thus eliminate the effects of fluctuations in this fraction, which limit the precision with which hadrons and jets can be detected in calorimeters. In the RD52 (DREAM) project, the possibilities of this dual-readout calorimetry are investigated and optimized. In this talk, the latest results of this project are presented. These results concern the first tests of the partially completed full-scale SuperDREAM fiber calorimeter, which were recently carried out at CERN.

Key words: Calorimetry, Dual-Readout, Čerenkov light

1. Introduction

In most modern high-energy physics experiments, the precision with which the four-vectors of single hadrons and jets can be measured is limited by fluctuations in the energy fraction carried by the electromagnetic shower component ($f_{\rm em}$) [1]. The RD52 Collaboration tries to do something about that. In our detectors, the mentioned fluctuations are eliminated by simultaneous measurements of the deposited energy and the fraction of that energy carried by relativistic charged shower particles. We have experimentally demonstrated that this makes it possible to measure $f_{\rm em}$ event by event [2]. We use scintillation light and Čerenkov light as signals for the stated purposes. Therefore, this method has become known as the Dual REAdout Method (DREAM). Since it is possible to eliminate fluctuations in $f_{\rm em}$, this method provides in practice the same advantages as intrinsically compensating calorimeters ($e/h = 1$), but is not subject to the limitations of the latter devices: Sampling fraction, signal integration time and volume, and especially the choice of absorber material. This has important consequences for the precision of jet measurements.

At this year's Vienna conference, we present the newest results of our R&D program. These concern measurements that were carried out just before Xmas at CERN, in which our partially completed new dual-readout fiber calorimeter (called SuperDREAM) was exposed to beams of electrons and hadrons. Since the data were only recently obtained, these results should be considered preliminary, and are likely to further improve in the future.

2. The SuperDREAM fiber calorimeter

Even though crystals also offer interesting possibilities [3], we believe that fiber-based detectors offer the most promising applications for dual-readout calorimetry. For this reason, we have embarked on a construction program that should produce a device that is sufficiently large to contain high-energy jets at a level where shower leakage fluctuations are *not* dominating the hadronic energy resolution. Based on measurements of the radial shower profiles, we estimate that a fiducial mass of 5 tonnes will be needed to contain high-energy hadron showers at our 99% target level. For reasons explained elsewhere [4], copper should be the preferred absorber material for such a detector.

Yet, it turned out that the absorber structures needed for the

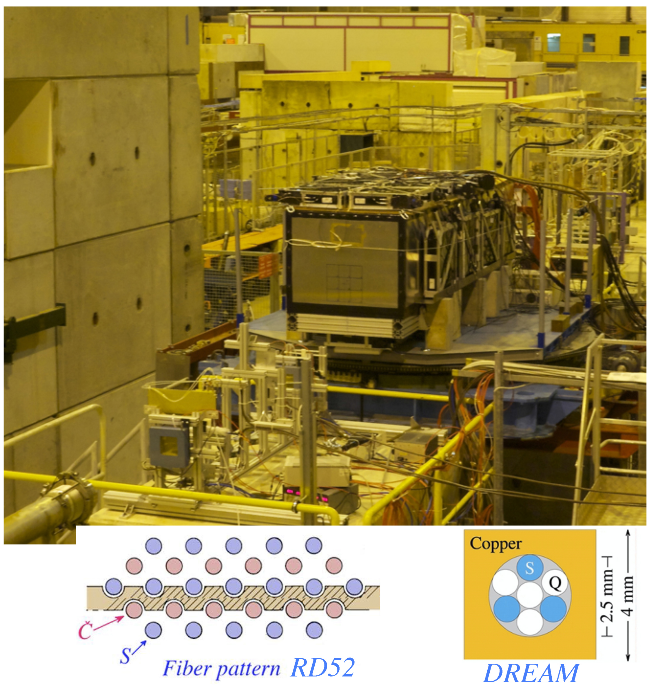

Figure 1: The partially completed RD52 fiber calorimeter during recent tests in the H8 beam line at the CERN SPS. The insert shows the fiber patterns in the RD52 calorimeter and in the original DREAM calorimeter.

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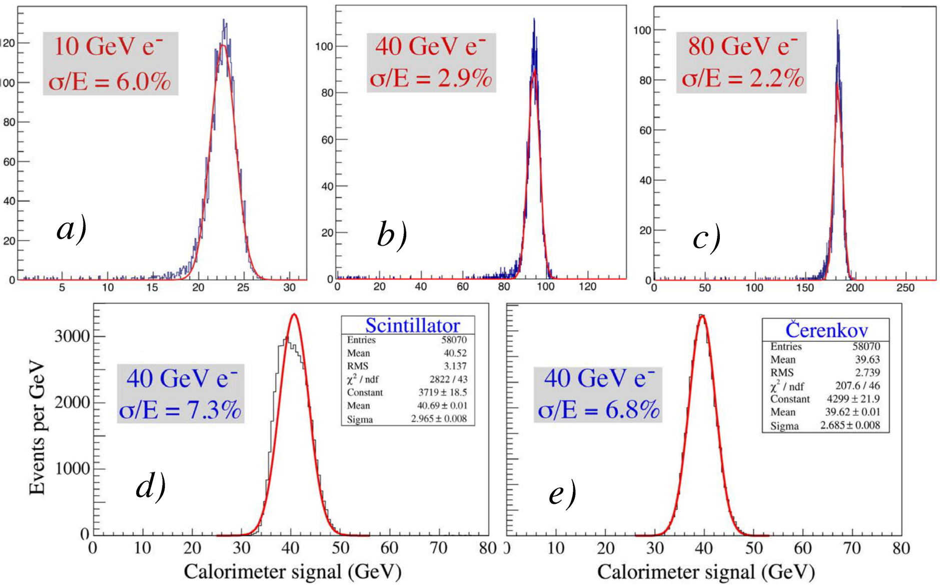

Figure 2: Response functions of the RD52 fiber calorimeter to electrons of 10 (*a*), 40 (*b*) and 80 (*c*) GeV, compared with the response functions of the DREAM calorimeter to 40 GeV electrons, in the scintillator (*e*) and Čerenkov (*f*) channels.

high-frequency sampling calorimeter we want to construct are not easy to make. For that reason, the first prototype modules have been made using lead as absorber material, since this is relatively easy to extrude. However, recently we have also managed to build a few modules out of copper.

Figure 1 shows a picture of the partially completed new fiber calorimeter while it was installed in the H8 beam line at CERN's Super Proton Synchrotron, where it was tested in December 2012 using beams of high-energy electrons and pions. The detector consisted of 11 modules (nine with lead absorber, two with copper). Each module measured 9.2×9.2 cm^2 in cross section and 250 cm in length ($\approx 10\lambda_{\mathrm{int}}$), and had a mass of $\sim$ 150 kg (120 kg for Cu), which gave the detector a total instrumented mass of a little less than 1.6 tonnes. Measurements of the radial shower profile showed that the showers initiated by 60 GeV π^- were, on average, contained at the level of 93.6% in this structure. Each module consisted of four towers (4.6×4.6×250) cm^3, and each tower contained 512 plastic optical fibers (diameter 1.0 mm, equal numbers of scintillating and clear fibers). Each tower produced two signals, a scintillation signal and a Čerenkov signal, which were detected by separate PMTs.

The main differences with the original DREAM fiber module concern the fact that each fiber is now individually embedded in the absorber structure, whereas the fibers were bunched together in groups of seven in the DREAM module. Also, the fiber density has been increased by about a factor of two. As a result, the contribution of sampling fluctuations to the energy resolution[1] has been reduced by a factor 2.2. The limit in the fiber packing fraction is determined by the fact that the readout (eight PMTs for reading out the four calorimeter towers of which each module consists) has to fit within the detector envelope. For that reason, we have chosen PMTs with a very large effective photocathode area[2].

3. Experimental results

One of the most important (and limiting) characteristics of this calorimeter is the Čerenkov light yield. In the lead-based modules, we measured this light yield to be $\sim$ 60 photoelectrons per GeV deposited energy, an increase by a factor of seven compared to the original DREAM module. The changes in the structure of the fiber module did indeed pay off in the form of a substantially improved em energy resolution. This is illustrated in Figure 2, where the response function of the RD52 calorimeter for electrons of different energies is shown together with the response functions for 40 GeV electrons in the original DREAM module [5].

One advantage of the new fiber pattern is the fact that the scintillation and Čerenkov readout represent completely independent sampling structures. Therefore, by combining the signals from the two types of fibers, a significant improvement in the energy resolution is obtained. This was not the case for DREAM, where the two types of fibers essentially sampled the showers in the same way. Another advantage derives from the greatly reduced distance between neighboring fibers. This makes the response (and thus the energy resolution) much less sensitive, if at all, to the impact point of the electrons. Because of the extremely collimated core of the em showers, there is a systematic response difference between particles entering the detector in the absorber material or in the fibers in this type of calorimeter. This difference is responsible for the non-Gaussian line shape of the scintillation signals in the DREAM calorimeter (Fig. 2d), an effect that gets rapidly worse when the angle

[1]This contribution scales like $\sqrt{d/f_{\mathrm{samp}}}$, where d represents the fiber thickness and f_{samp} the sampling fraction [1].

[2]Hamamatsu R8900, 10-stage, super bi-alkali photocathode

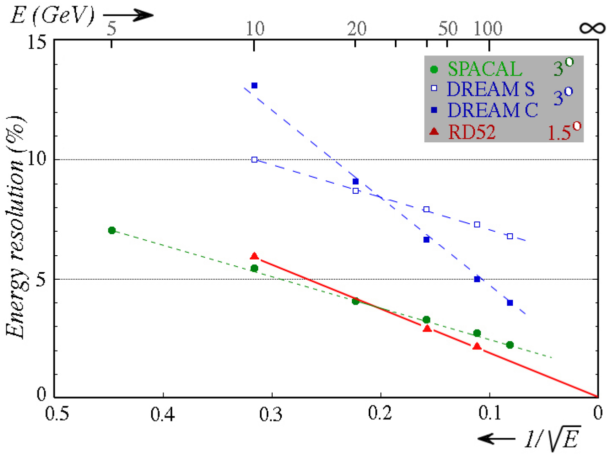

Figure 3: Comparison of the em energy resolution measured with the RD52 fiber calorimeter, the original DREAM calorimeter [5], and the SPACAL fiber calorimeter [6].

of incidence of the particles approaches 0°. Interestingly, this effect is absent for the Čerenkov signals. This is because the very collimated, narrow core that characterizes the early phase of em showers does *not* contribute to the Čerenkov signals, since the Čerenkov light generated in this phase falls outside the numerical aperture of the fibers [5]. Because of the very small distance between neighboring sampling layers (fibers), this impact point dependence is almost completely absent for the RD52 calorimeter. This is illustrated by the fact that the energy resolution scales perfectly with $E^{-1/2}$ (Figure 3). In more crudely sampling fiber calorimeters such as DREAM [5] and SPACAL [6], the energy resolution clearly exhibits a deviation from $E^{-1/2}$ scaling as a result of the mentioned effect[3]. At energies above 20 GeV, the em energy resolution is clearly better than that of any of the other mentioned fiber calorimeters. Further improvements may be expected when the effects of the upstream preshower detector are taken into account.

Analysis of the hadronic performance is still in an early stadium. Effects caused by light attenuation in the fibers and lateral shower leakage have yet to be taken into account. Yet, initial results are very encouraging, as illustrated by Figure 4. It has been shown [7, 8] that the energy E of a hadron in a dual-readout calorimeter can be found in the following way:

$$E = \frac{S - \chi C}{1-\chi} \quad \text{with} \quad \chi = \frac{1-(h/e)_S}{1-(h/e)_C} \qquad (1)$$

where S and C represent the scintillation and Čerenkov signals measured for each event, and χ is a parameter that is characteristic for the calorimeter, determined by the e/h values of the scintillating and Čerenkov caloirmeter structures. For example, for the original DREAM calorimeter these e/h values were measured to be 1.3 and 4.7, respectively, which led to a χ value of 0.29. For RD52, the best results were found for $\chi = 0.26$, which is no surprise if one considers that the e/h value is closer to one for scintillator calorimeters with high-Z absorber material [1]. The signal distributions in fig. 4 are well described by Gaussian functions, and the average values are close to the beam energies. Figure 5 shows that the energy resolutions are considerably better than for single pions measured

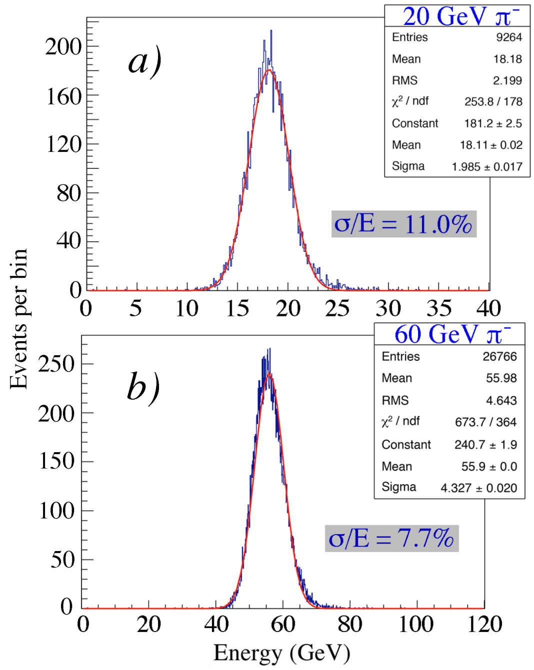

Figure 4: Preliminary response functions of the partially completed RD52 fiber calorimeter to 20 (a) and 60 (b) GeV π^-. No corrections for light attenuation and shower leakage were applied.

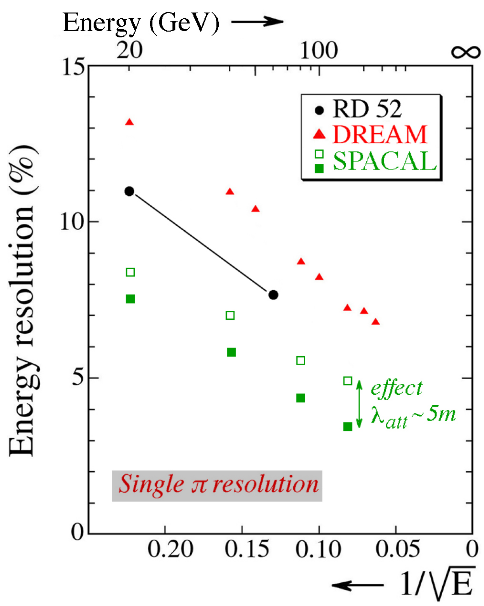

Figure 5: Comparison of the preliminary energy resolution obtained for single pions with the partially completed RD52 fiber calorimeter, and the published resolutions for single pions obtained with the DREAM calorimeter [2] and with the SPACAL fiber calorimeter [6]. The latter results are shown before and after correcting for light attenuation effects in the scintillating fibers.

[3] Expressed in Moliere radii (ρ_M), the distance between neighboring fibers is $0.022\rho_M$ in RD52, $0.099\rho_M$ in DREAM and $0.071\rho_M$ in SPACAL.

in the DREAM calorimeter. They are not yet at the level of the compensating 20-tonnes SPACAL calorimeter, which holds the world record in this domain [6]. Based on the results obtained with the latter instrument, a significant improvement of the RD52 resolutions may be expected from taking into account the effects of light attenuation in the fibers.

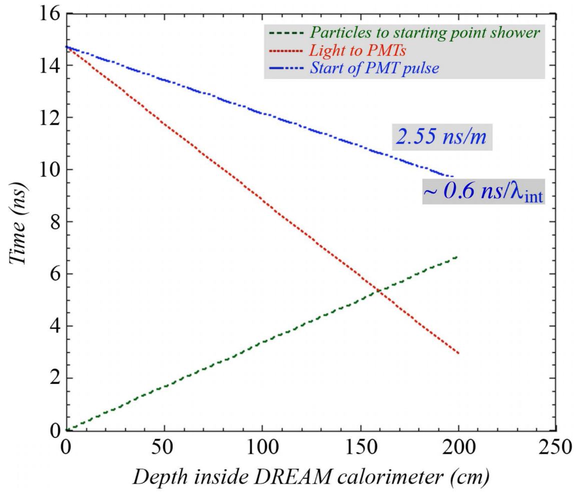

Figure 6: The dependence of the starting time of the PMT signals on the depth (z) inside the calorimeter at which the light is produced. Also shown are the time traveled by the beam particles from the front face of the calorimeter to this depth z and the dependence of the time traveled by the light through the fibers from z to the PMT.

To measure the light attenuation in the two types of fibers, a new method has been tried out for determining the depth at which the light was produced in the fiber calorimeter. A crucial aspect of this type of calorimeter is its *longitudinally unsegmented* structure. However, the detailed time structure of each event makes it possible to obtain crucial information about the depth at which the light is produced. By using the fact that light travels at a speed of c/n in the fibers, while the particles producing the light travel at c, the starting time of the signals makes it possible to measure the depth at which the light is produced with a resolution of $\sim$ 20 cm, as illustrated in Figures 6 and 7.

Apart from allowing corrections for light attenuation in the fibers, the measurement of the depth of the light production in

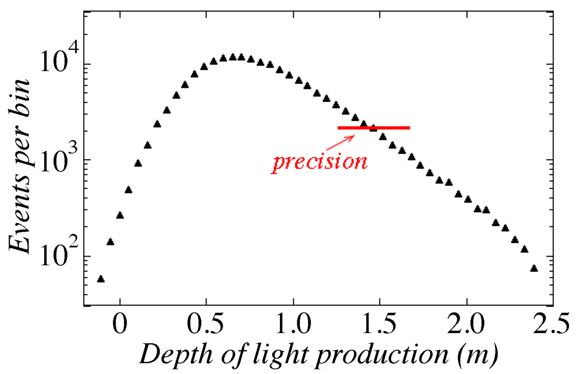

Figure 7: Event-by-event distribution of the depth at which the light is, on average, produced inside the calorimeter by the beam particles (60 GeV π^-).

this longitudinally unsegmented calorimeter may also turn out to be useful for other purposes, in particular

1. Particle identification. Electrons may be recognized since they always produce light in the first 20 cm of the calorimeter module. In addition, the time structure of the signals is always the same, and significantly different from that of hadronic signals. The characteristic lateral shower profile offers a handle as well. A separate paper on this topic is in preparation.
2. The depth measurement in several towers contributing to the shower signal may provide an indication of the direction at which the particle(s) entered the calorimeter, thus allowing measurement of the entire four-vector.

As shown elsewhere [9], the time structure, measured with a Domino Ring Sampler operating at 5 GHz [10], is also an important tool for measuring the neutron contribution to the scintillation signals.

4. Conclusions

Dual-readout detectors hold the promise of high-quality calorimetry for *all* types of particles, with an instrument that can be calibrated with electrons. It provides a simple recipe for combining the signals from two active media, and this recipe yields a hadron response that is linear with energy, a Gaussian hadron response function centered around the correct value, and a good hadronic energy resolution, both for single hadrons and for jets. Our future plans in the context of RD52 include studies of adapting the fiber readout to the demands of modern 4π experiments, *e.g.,* by using silicon photomultipliers, a denser overall structure and projectivity.

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